

Review

APPLICATION OF BOTANICAL PESTICIDES IN ORGANIC AGRICULTURE PRODUCTION: POTENTIAL AND CHALLENGES

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Abstract. In agricultural pest management, botanical pesticides are most suitable for use in organic food (agricultural) production due to their safety to humans and the environment compared to conventional pesticides. Compounds of plant origin can be highly effective, with diverse and multiple mechanisms of action, and with low toxicity towards non-target organisms. Botanical pesticides (plant-derived pesticides) meet almost all of the requirements of organic agriculture and are therefore often used as an alternative for conventional pesticides in sustainable agricultural development. Using botanical materials to produce environmentally friendly pesticides and applying botanical pesticides to pest control in organic farming is also a potential development trend. Botanical products often contain plant extracts from different parts of plants possessing a variety of biological activities and the plant extracts are often composed of many environmentally friendly compounds such as essential oils (EOs), flavonoids, acetogenins, alkaloids, triterpenoids, phenolic acids, fatty alcohols, and vegetable oils. Botanical pesticides also exhibit various modes of action, are easily biodegradable, and have fewer residues and low toxicity to mammalian and non-target organisms. The raw materials used for the production of botanical pesticides are plant extracts, phytochemicals, and essential oils produced from medicinal plants and widely cultivated crops of pesticidal plants; therefore, they are readily available, abundant, and renewable. However, the large-scale application of these products for pest control is limited by their poor stability and other technological issues. An overview of botanical pesticides is presented in this paper. Trends and challenges in the research and application of botanical pesticides in Viet Nam are also discussed.

Keywords: botanical pesticides, plant disease, insects, weeds, phytopathogens.

Classification numbers: 1.1, 1.4.5.

1. INTRODUCTION

In recent years, the use of pesticides in the world has increased greatly due to the increasingly serious pests in agriculture. However, synthetic pesticides are often toxic and persist for a long time. Therefore, their inappropriate and uncontrolled use will cause many serious consequences, adversely affecting the environment and public health. In particular, the accumulation of residues and toxic substances in agricultural products and food, the reduction of biodiversity and natural resources (land, water, biological systems, etc.) have caused negative consequences on natural disasters and climate change, and the resistance in pests. To minimize the negative impacts of pesticides on the environment and society, the trend of using natural products, including botanical pesticides, is developing increasingly to gradually replace chemical products. Their main advantages are selectivity, low toxicity to humans, livestock and natural enemies, rarely causing resistance, biodegradable and no residues in agricultural products and the environment. Botanical pesticides are also a suitable choice in integrated pest management (IPM) programs and in organic agricultural production to develop sustainable agriculture [1].

Viet Nam is an agricultural country with a large cultivated area, favorable climatic conditions and a wide variety of crops, so pests develop in diverse ways all year round, leading to an increased demand for pesticides. However, Viet Nam is at the stage of developing green, safe and sustainable agriculture and applying the criteria for organic agriculture production established by IFOAM regulations (International Federation of Organic Agriculture Movements) which avoid or eliminate the use of most synthetic fertilizers and pesticides. This means increasing the use of environmentally friendly, natural agrochemicals to minimize potential risks and their negative effects on the ecological environment and public health.

2. USE OF BOTANICAL PESTICIDES IN ORGANIC AGRICULTURE PRODUCTION

The pesticide application must meet the criteria of organic agriculture production. Pesticides of plant origin (botanical pesticides) meet almost all of the above requirements and are therefore often used as an alternative for conventional pesticides in sustainable agricultural development. Using botanical materials to produce environmentally friendly pesticides and applied botanical pesticides to pest control in organic farming is a potential development trend. Botanical products often contain extracts from different parts of plants, essential oils (EOs), and vegetable oils, the chemical composition of which contains many environmentally friendly compounds with different biological activities [2].

Advantages and limitations of botanical pesticides could be figured out as bellows:

Advantages: Sources of raw materials used for the production of botanical pesticides are extracts and essential oils from different parts of plant, which are readily available, abundant and renewable. As mentioned above, botanical pesticides exhibit various modes of action, easily biodegradable, fewer residues, low toxicity to mammalian and non-target organisms. In addition, it is difficult to develop pesticide resistance since they contain a mixture of many substances, the effects of which can be attributed to different activities on pests included in the influence on behavioral and physiological processes of pests.

Limitations: Most of the plant-derived compounds are quickly and easily decomposed under environmental conditions. They have complex structures that are difficult to be synthesized, leading to high costs. Moreover, the slow-acting properties make some farmers impatient with the products. On the other hand, the product is a complex mixture of many chemical constituents

with low contents and varies depending on the regional distribution of plant, causing difficulty for the selection of extraction and purification technology as well as the product registration. Besides, the raw material source is not concentrated, which makes it difficult to ensure sufficient supply for production on an industrial scale. The practical application of botanical pesticides is still limited, only a few active substances are industrially manufactured and used, such as nicotine, rotenone, pyrethroid, matrine and azadirachtin [3]. Therefore, despite many advantages over synthetic products, the market for botanical pesticides is still small and limited. These challenges need to be solved in the near future. In addition, the use of botanical pesticides depends on many factors, such as the source of the raw material, technology and solvents for the extraction, storage stability of the products; knowledge and habits of farmers; demand and consumption market; etc.

Particularly in India and China, botanical pesticides have recently received great attention and development. Some of the botanical substances are known as semiochemicals, including pheromones, allomones, kairomones, and biochemicals (such as attractants, and repellents). Some of them can change the behavior of insect pests without killing them. Many EOs and their constituents have chemosterilants, e.g., asarone extracted from the rhizome of *Acorus calamus* possesses antigonadal activity, causing complete inhibition of the ovarian growth of various insects [4]. EOs also have physico-chemical properties that are useful as solvents and additives in pesticide formulation. Thus, plant-derived products have high potential applications. These products can be extracts or EOs obtained from different parts of plant such as leaves, bark, flowers, roots, rhizomes, etc. However, the low content of active ingredients in different parts of the plant is still a challenge for extraction and purification techniques. Therefore, the practical scope of natural pesticides is limited and only a few are industrially produced and are widely used.

2.1. Botanical insecticides and their classification

The insecticidal activity of some plant species has been discovered thousands of years ago. Since the years before Christ, the ancient Chinese and Egyptians knew how to use a range of plants to control insects, flies, and mosquitoes. Botanical insecticides have also been used in Europe for a long time. In the 17th century, farmers used *Nicotiana tabacum* infusions containing nicotine to kill pests and strychnine in the seeds of *Strychnos nux-vomica* to kill rats. In the 19th century, rotenone, obtained from the roots of *Derris elliptica* and pyrethrum from *Chrysanthemum*, were used as an insecticide (Table 1). Today, nearly 2000 plants with insecticidal properties are known, but unfortunately, only a few of them have been properly evaluated and practically used. In Vietnam, according to a recent report, there are around 335 plant species, of which over 10 species have the best insecticidal activities [3].

Botanical insecticides can be divided into two generations: the first generation contains nicotine, rotenone, sabadilla, ryanodine, pyrethrum and some EOs from plants. The second generation includes azadirachtin and compounds of the genus *Melia* spp., and new potential plants such as *Annona* spp., *Pongamia pinnata*, *Artemisia douglasiana*, *Piper nigrum*, *Allium sativum*, *Flacourtiaceae*, *Centaurea maculosa*, etc. [5 - 7]

Toxicity of botanical insecticides

Many botanical insecticides are selective and low in toxicity to humans and mammals but are highly toxic to insect pests. Most EOs from plants and similar products have acute toxicity of

more than 2 g/kg by ingestion and contact for both oral and dermal application while being non-toxic to mammals, birds and fish. However, due to its broad-spectrum activity, they may cause harmful effects to bees and natural enemies. According to the available information, most EOs and their main constituents have been reported to be not mutagenic/genotoxic. The terpenoids of some EOs have moderate toxicity to mammals, while others are known to have molluscicidal activity. Given that any residues on plants are minimal (due to the fumigation and degradation properties), numerous EOs are insufficient to be considered as high-risk substances [8].

Table 1. Mode of action of botanical insecticides [7 - 10].

Compound	Source	Mode of actions
<i>Plant-derived compounds</i>		
Nicotine	<i>Nicotiana</i> spp.	Binding to nicotinic acetylcholine receptor (nAChR) at synapses, causing uncontrolled neuronal firing.
Pyrethrin	<i>Crysanthemum cinerariaefolium</i>	Disrupting Na ⁺ and K ⁺ exchange process in insect nerve fibers and interrupting the normal transmission of nerve impulses.
Rotenone	<i>Derris</i> spp.	Inhibition of cellular respiration, causing paralyze the respiration function
Ryanodine	<i>Ryania</i> spp.	Affecting on calcium channel
Sabadilla	<i>Schoenocaulon officinale</i>	Affecting and causing loss of nerve cell membrane action, loss of nerve function, paralysis and death
Azadirachtin	<i>Azadiractina indica</i> (Neem tree)	Disrupting hormonal balance. Inhibiting the activity of acetylcholinesterase (AChE)
<i>Essential oils (EOs) and their constituents</i>		
EOs	<i>Mentha</i> spp. <i>Lavendula</i> spp. <i>Cedrus</i> spp. <i>Pinus</i> spp. <i>Citronella</i> spp. <i>Eucalyptus</i> spp.	Inhibition of enzyme AChE
Thymol	<i>Thymus vulgaris</i>	Affecting on the neuroregulatory octopamine receptor
Citrus Oil Extracts (D-Limonene, Linalool)	<i>Rutaceae, Meliaceae</i>	Disrupt the functioning of the GABA synapse. Block octopamine receptors by working through tyramine receptors cascade
Dillapiole	<i>Anethum sowa</i>	The mechanism is unknown but it is probably the inhibition of enzyme AChE
Piperine, Piperamides	<i>Piper</i> spp.	Inhibition of cytochromes P450 (CYPs)
Eugenol	<i>Syzygium aromaticum, Ocimum gratissimum</i> L.	Affecting on the neuroregulatory octopamine receptor
Carvacrol	<i>Origanum vulgare</i>	Binding to nicotinic acetylcholine receptors (nAChR)
1,8-Cineol	<i>Rosmarinus officinalis</i>	
Cinnamaldehyde	<i>Cinnamomum</i> spp.	Octopamine receptor antagonist
Citronellal	<i>Cymbopogon nardus</i>	

Modes of action of botanical pesticides

As a natural evolution, many secondary metabolites in plants are formed to fight harmful enemies, to help plants survive and grow. However, studies on the modes of insecticidal action of those chemicals are difficult due to the complexity of the composition. They exhibit diverse biological activities and play different roles in the mixture. Through many published research reports, there is evidence that most botanical insecticides affect the nervous system of insects through contact, oral or inhalation route, causing loss of central nervous system function, paralysis and death quickly [3]. In 2013, Nabil E. *et al.* outlined the modes of action of some active ingredients in plants and EOs used as botanical insecticide (Table 1). According to the author, there is evidence of a disruption of the neuromodulator octopamine and the main neurotransmitters of the central nervous system (GABA chloride) are caused by some substances in plants and EOs [7]. The main modes of action of botanical insecticides are shown in Table 1.

2.1.1. Non-volatile phytochemicals with insecticidal activity

Many botanical insecticides have been produced and commercialized for a long time. The first generation was nicotine, contact insecticide to control *Phyllocnistis citrella*, rotenone and rotenoid with insecticidal and acaricidal activity; ryanodine to control green worm and stem borers; sabadilla, derived from the seeds of *Schoenocaulon officinale* with a broad-spectrum activity for planthoppers, fleas, thrips and aphid control; pyrethrins, a mixture of 6 compounds in extracts of *Chrysanthemum cinerariaefolium* flowers with fast-acting and broad-spectrum activity. In which, sabadilla is considered to be the least toxic botanical insecticide with LD₅₀ of about 4000 to 5000 mg/kg. Later, azadirachtin and several other products from Indian neem seeds (*Azadirachta indica*) became the most widely used botanical pesticides in the world. Azadirachtin has a wide spectrum of action with insecticidal and nematocidal properties.

Recently, some new plant-derived products have been used in practice. Karanjin, a furanoflavonol from *Pongamia pinnata* is used in pest control with insecticidal, acaricidal, antifeedant and repellent activities. Matrine extracted from *Sophora flavescens* is a broad-spectrum insecticide and antifeedant, repellent for control sucking and biting insects [2]. Allicin from garlic (*Allium sativum* L.) has high activity on the snail *Acuminata* [11]. Saponins contained in different plant species, such as soapberries, tea, quinoa, etc., exhibits activity against golden apple snail (*Pomacea canaliculata*) in rice fields, replacing the synthetic product niclosamide [12, 13]. Vulgarin in *Artemisia douglasiana* provides antibacterial activity but can also kill yellow apple snail within 24 hours [14].

2.1.2. Essential oils with insecticidal activity

In addition to the above-mentioned extracts, EOs, used in plant protection, have received a lot of attention recently. EOs are distinguished from other vegetable oils by their volatility and occupy an important position in botanical pesticides. Many of their constituents showed a broad spectrum of activity against insects (insecticidal, antifeedant, repellent, oviposition deterrent activities) and were used in practice. EOs are complex mixtures of different organic volatile compounds and belong to various chemical classes: alcohols, ethers or oxides, aldehydes, ketones, esters, amines, amides, phenols, heterocycles, and mainly the terpenes. These oils are generally liquid and colorless at room temperature, with a characteristic odor. They are soluble in alcohol, ether and fats, but insoluble in water. Most of them have biological activity and are used in different industrial applications. Many EOs from the families Lamiaceae, Myrtaceae, Asteraceae, Rutaceae, Apiaceae and Laureaceae have insecticidal, antiviral, antibacterial and antifungal activity [2].

Essential oils are commercially produced from different medicinal and aromatic plants. They consist of a complex mixture of volatile and lipophilic compounds containing around 20 to 60 components, the major two or three of which at high concentrations determine the biological properties of the EOs. Compounds in EOs can be divided into two groups: phenylpropanoids with low molecular weight and terpenoids (monoterpenes, sesquiterpenes) [15], for example, 1,8-cineole, the main component of rosemary oils (*Rosmarinus officinale*); eucalyptus (*Eucalyptus globus*); eugenol from basil oil (*Ocimum gratissimum* L.) and clove oil (*Syzygium aromaum*); thymol from thyme (*Thymus vulgaris*); menthol from *Mentha* spp., etc. Initially, some EOs have been used in post-harvest pest control [16]. When the toxicity by fumigant and contact of essential oils were discovered and evaluated, interest in this area significantly increased [9,10]. The biological activity of EOs on insects limits their reproductive potential by inhibiting the reproductive cycle. For example, canola oil from *Brassica napus* L., jojoba oil from jojoba seeds, capsaicin oil from *Capsicum* spp., etc. possess insecticidal activity. Some others, like the EOs of thyme (*Thymus vulgaris*), rosemary (*Rosmarinus officinalis*), eucalyptus (*Eucalyptus saligna*) also have antifeedant or repellent activities, such as *Cymbopogon nardus* essential oil repelling mosquitoes and flies, and garlic (*Allium sativum*) oil-deterrent for many insects [17].

Moreover, the accessibility of extraction and environmentally friendly property due to rapid decomposition and low toxicity to mammals and fish lead to the recent recognition of many EOs as important natural products used in crop protection, post-harvest pest control and public health. Currently, more than 60 EOs are considered safe organic pesticides in the United States and are exempt from registration with the Environmental Protection Agency (EPA). They are recommended for use in horticulture and greenhouses as well as for domestic use in the United States and the United Kingdom [17].

2.1.3. Fatty acids and derivatives with insecticidal activity

In vegetable oils, there are about 8 fatty acids from C12 to C18 that have insecticidal activity, including some saturated acids such as caprylic, lauric, myristic, palmitic, stearic and unsaturated acids such as oleic, linoleic, and linolenic acid. For example, linoleic acid, oleic acid, linolenic acid, palmitic acid, and stearic acid are effective against the *Spodoptera frugiperda*, *Helicoverpa armigera*, and the red spider *Tetranychus cinnabarinus*. Other fatty acids have also been used as insecticide or repellent against household pests (mosquitoes, cockroaches, ants, etc.). Fatty acids interfere with the cell membrane constituents of the target organism, leading to a breakdown of the integrity of the membrane and subsequent death. Sorbitol octanoate is effective against aphids and molluscs in agriculture due to its surfactant properties. The glycerol and propylene glycol of caprylic, capric, and lauric acid have been approved by the U.S. Food and Drug Administration (FDA) since 2003 for use to eliminate ticks and bacteria in post-harvest pest control. Some fatty acid methyl esters are commonly used as surfactants, synergists or additives in pesticide formulations [18].

2.2. Botanical pesticides with non-toxic mode of action (Biochemical pesticides)

The US EPA considers the term “non-toxic mode of action” to imply that no chemical or biological interaction of the biopesticide molecule occurs with the physiology of the target pest organism such that direct lethality results in that pest organism [19]. Biochemical pesticides and semiochemicals with non-toxic mode of action are used in pest control for reducing the risk, pollution and resistance of pesticides. Semiochemicals are organic compounds that act as signals and enable intra- and inter-specific chemical communication. They are species-specific and

harmless to the environment. These advantages over conventional pesticides make semiochemicals promising tools for the management of agricultural pests, particularly in organic cropping systems [20]. Biochemical pesticides include all naturally occurring substances (or their structurally similar synthetic analogs) that are intended for use as attractants, repellents, antifeedants, chemosterillants, plant and insect growth regulators, desiccants, etc. The systematic study of these products only began in the second half of the 20th century, with research on biological and behavioral insect gaining interest and development [3].

2.2.1. Attractants and pheromones

Insect attractants include food-based attractants and sex attractants, where special sex attractants use a variety of plant-derived products. In addition, it has also been found that many insects have an oviposition preference and select suitable plants to secrete certain chemical compounds to lay eggs (Oviposition attractants). For examples, Brassicaceae plant, Garden Nasturtium (*Capucine* spp.), Wild mignonette (*Reseda* spp.), and Mustards (*Cruciferae* spp.) contain an isothiocyanate derivative, which is able to attract *Pieris rapae* to come for ovipositing. Similarly, white cabbage leaf juice *Sinapis* attracts silkworm *Plutella maculipennis*. Some plant oils and EOs are particularly attractive to insects, e.g. natural phenol-ethers such as eugenol from basil, anethol from anise oil or terpenic compounds such as geraniol from lemongrass oil, α and β -ionons in a variety of essential oils, including rose oil. The mixture of eugenol and anethole attracts the male scarab *Papillia japonica* [3]. EOs and some extracts of rosemary *Rosmarinus officinalis* in polar solvents attract the moth *Lobesia botrana*. Orchids of various *Bulbophyllum* species attract male fruit flies *Bactrocera* by releasing volatile substances such as raspberry ketone and methyl eugenol for pollination in humid forests of Southeast Asia [21].

The general characteristics of insect attractants are volatile such as alcohols, esters or ethers, having a relatively complex molecular structure in which only a small change can lead to loss or a significant decrease in biological activity. The dosage is very low (about $\leq 10^{-5}$ $\mu\text{g/mL}$) so that the purity of the active ingredient needs to be very high. Since the synthesis or extraction of these compounds is complicated, they are often expensive and used only in some areas such as phytosanitary, public health, integrated pest management programs (IPM), etc. [22].

Pheromones are chemical signals used to communicate between members of the same species. Among the numerous roles that have been elucidated for pheromones include attraction, aggregation, aphrodisiacs, anti-aphrodisiacs, kin recognition, and alarm signaling. The sex pheromone is the most studied and widely used in insect pest management than other pheromones [22]. Recently, there has been a trend towards finding and using pheromones from plants for research and practical application. In 2011, Marianne Müller *et al.* compiled studies regarding pheromones consisting of essential oil components of various aromatic plants and released by insects and arachnids. For example, verbenol and verbenone were an essential part of the bark beetle's aggregation pheromone, released with the intent to round up its conspecifics. Nepetalactol and nepetalactone, two components from EO of the catnip (Lamiaceae), occur as sex pheromones secreted by bed bugs to stimulate mating. Some bees mimic a linalool-containing orchidsodour as their sex pheromone and thus attract their mating partners. Studies about termite show that a number of different pheromones also appear as EO components, e.g., neocembrene (from turpentine) as a part of the trail pheromone; (*E,E*)- α -farnesene (from apple, gardenia) as an alarm pheromone; sand flies use derivatives of α -himachalen (contained in forest pudding apple), germacrene D (in the ylang-ylang EO) or cembren from turpentine as sex pheromones (Figure 1) [23].

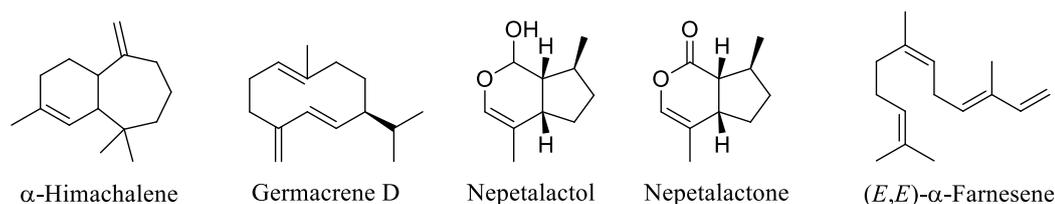


Figure 1. Chemical structure of some pheromones from EOs.

2.2.2. Insect repellents

Repellents are substances that deter or repel arthropod insects without necessarily being toxic to them. Insect repellents have been used since ancient times, but systematic research did not develop until after World War II, when the need to protect troops from malaria, yellow fever, etc. increased. Currently, insect repellents have received more attention, especially to protect people and pets from household insects such as flies, mosquitoes, ticks, bed bugs, etc. and to be used in phytosanitary [24]. The most desired characteristics of a commercial insect repellent are long-lasting effects (protection time) and independent of weather conditions; non-toxic to humans and the environment; no unpleasant odors and no influence on materials impregnated as clothing, mosquito net, etc. [3]. Many commercial synthetic repellents such as *N,N*-diethyl-*m*-toluamide (DEET), icaridin (picaridin), permethrin are highly effective and persistent but cause environmental and human health risks, especially for children [25]. An alternative is to use natural products that are effective and environmentally friendly. Some plant-based repellents like EOs are comparable to, or even better than, synthetics.

The mode of action: Despite their common use, the mode of action of insect repellents is not fully understood and is explained by many hypotheses. But the general theories can be as follows: Human sweat contains several substances that attract sucking insects (mosquitoes, bed bugs), of which lactic acid may be the strongest. Repellents act on insects by interacting with the olfactory receptor (OR) and gustatory receptor (GR), making them unstimulated by lactic acid and disoriented, unable to find a host to burn and suck blood. In addition, using rapid biochemical screening assays and bootstrap analysis on the inhibition analysis revealed a significant correlation between P450 enzyme inhibition and repellent activity of some EOs. Usually, insect repellents work by providing a vapor barrier deterring the insects from coming into contact with the surface [25].

Plant-based repellents containing several alkaloids from the *Berberidaceae*, *Solanaceae*, *Ranunculaceae*, and *Fabaceae* families, are widely used as traditional repellents. However, most are toxic to the mammalian nervous system, so their use is limited [24]. EOs from a large number of plants have been found to have significant repellent properties against various arthropods. Since EOs are mixtures of volatile organic substances, including hydrocarbons with a diversity of functional groups, their repellent activity has been linked to the presence of monoterpenes, sesquiterpenes and oxidized compounds (alcohols, esters, ethers, aldehydes, ketones, etc.). In some cases, these chemicals can work synergistically, improving their effectiveness. Within the plant families with promising EOs used as repellents, *Cymbopogon* spp., *Ocimum* spp. and *Eucalyptus* spp. are the most effective. Individual compounds present in these mixtures with high repellent activity include: α -pinene, limonene, linalool, linalol, citronellol, citronellal, camphor and thymol. Among them, citriodiol (*p*-menthane-3,8-diol) from Lemon eucalyptus (*Corymbia citriodora*) has long-lasting repellent effects and therefore provides good protection from mosquito-borne diseases. In addition, some other EOs have

repellent effects such as melaleuca, royal sandalwood (cedar), cinnamon, cloves, pepper, garlic, celery, castor oil, lavender, rosemary, thyme, wormwood, and guava flowers [26, 27].

The main disadvantage of insect repellent from EOs is its short protection time due to the high volatility. To overcome, several solutions could be considered for enhancing the repellency, e.g., development of new formulations or the use of additives or synergist and mixture of different active ingredients. To extend the repellency duration, cream-based, polymer mixtures based or microcapsules formulation can be applied for controlled release. In order to increase EO repellent efficiency, some fixative materials such as liquid paraffin, vanillin, salicylic acid, mustard and coconut oils have been used [27].

Finally, from an economical point of view, synthetic chemicals are still more frequently used as repellents than EOs, these natural products have the potential to provide more efficient and safer repellents for humans and the environment.

2.2.3. Antifeedants

Any substance produced by plants (plant secondary metabolites) that reduces consumption (feeding) of an insect can be considered an antifeedant or feeding deterrent. Antifeedants often have an unpleasant taste, directly acting on the taste organs of insects, making the insects not want to eat.

Mode of action of most antifeedants is focused on the taste cells. Although most antifeedants likely act by stimulating a deterrent receptor, that in turn sends a signal to the feeding center in the insect's central nervous system, some antifeedants are thought to block or otherwise interfere with the perception of feeding stimulants, whilst others may cause erratic bursts of electrical impulses in the nervous system preventing the insect from acquiring appropriate taste information on which it may choose an appropriate feeding behavior [28].

The use of antifeedants is one of the methods of crop protection, interested since the last decades of the 20th century and they are considered a biopesticide. Antifeedants can be found amongst all the major classes of plant secondary metabolites such as alkaloids, phenolics and terpenoids, of which terpenoids are the most important. For instance, thymol in *Thymus vulgaris*, polygodial in *Polygonum hydropiper*, abietic acid in *Pinus* spp., azadirachtin in *Azadirachta indica*, aginoside in *Allium porrum*, strychnine in *Strychnos nux-vomica*, tomatine in *Lycopersicon esculentu*, methyl salicylate in *Gaultheria procumbens*, etc. are effective antifeedants [29]. In recent years, antifeedant approach for insect control has been extensively studied, yielding promising results. Many plant-based compounds and EOs have been shown to have antifeedant effects, namely α -terpinene, *trans*-cinnamaldehyde, citronellal and 1,8-cineole as potent antifeedants on cotton leafworm *Spodoptera littoralis*, *Helicoverpa armigera* and *Achaea janata* [30, 31]; (1S)(-)-verbenone, (\pm)-camphor and linalyl acetate showed moderate activity on *Leptinotarsa decemlineata* [32].

However, the use of antifeedant in crop protection also has limitations. If used indiscriminately, it may result in the development of resistance in insects and the efficacy is greatly reduced. Another operational problem specific to antifeedants is the potential for rapid desensitization to a feeding deterrent. Individual insects, initially deterred by a feeding inhibitor, become increasingly tolerant upon repeated or continuous exposure. In fact, the feeding deterrent activity makes insects become habituated and cross-habituated which is a drawback. However, it can be mitigated by using mixtures of antifeedants in a multicomponent strategy, e.g., the combination of xanthotoxin and thymol [28].

2.2.4. Insect growth regulators (IGR)

Hormones are substances that interfere with the growth, development and state changes of insects. In insects, there are 3 main types of hormones: shedding hormone ecdysone (Moulting Hormone-MH), rejuvenating hormone (Juvenile Hormone-JH) and neurohormonal humoral hormone (brain hormone) also known as Activating Hormone (AH). Among these, rejuvenation hormone, which helps insects' transition from full-fledged larvae to pupation and molting through age, is most studied. Mastering these properties, humans have used the available hormones of insects or synthetic substances to inhibit the growth and development of insects (inhibition of chitin synthesis-CSI). In addition, people also use anti-hormonal substances (anti-hormone) to prevent the formation of hormones, so that the insect does not pass a certain stage of development and then dies [33].

Plant-derived insect growth regulators have been studied for many years. In 1993, A. K. Jactive *et al.* published the bioassay of 33 species of plants belonging to 18 families of angiosperms. Among the 9 plants with JH activity, the extracts from the bark and leaves of *Callistemon lanceolatus* and *Gynandropsis gynandra* provided the highest activity. Other active plants were *Ocimum sanctum*, *O. basilicum*, *Curcuma longa*, *Psidium gaujaya* and *Mentha longifolia* [34]. Plants also carry many compounds which act as CSIs, such as plumbagin, a naturally occurring CSI present in the roots of tropical medicinal shrub *Plumbago capensis* which inhibits ecdysis in several Lepidopteron pests including *Helicoverpa* spp. Plumbagin derivatives and possess high ovicidal activity against eggs of different stages of *Dysdercus koenigii*. Azadirachtin, potent neem-based CSI, limits the reproductive potential of stored product insect pests [35].

IGRs generally have high selectivity; low toxicity to mammal and non-target organism, including invertebrates, fish, birds, and other wildlife, and do not adversely affect the biological population. However, some disadvantages when using JH is that they harm insects only at a particular stage of development, not affecting other stages and are not stable under environmental conditions (light, wind). IGRs have great potential for insect control but is more expensive to synthesize, environmentally instable, and narrow host range limits their commercialization [35].

In Viet Nam, pesticides based on insect growth control have been used, but they are all synthetic and imported products. No plant-based product has been studied and used in practice.

2.3. Botanical fungicides

For many years, the use of toxic synthetic fungicides such as carbendazim, captafol and hexachlorobenzene has been effective in controlling plant diseases, but some negative issues arose such as hazardous impacts on human health and the environment, as well as the development of resistance and toxic residues in agricultural products. Plant-derived products have been found to be effective, selective in plant disease management and could be safely incorporated as suitable alternatives for synthetic fungicides. It is estimated that more than 250,000 species of plants can be evaluated for chemical compounds with antimicrobial, antifungal activity. Many plant extracts, EOs, gums, resins, etc. have biological activity against plant pathogens and can be used as botanical fungicides. These products generally have low ecotoxicity, low residue and are safe for humans, so they are often used in IPM programs to control plant diseases. They can be easily adopted by farmers in developing countries who have traditionally used plant extracts for the treatment of human diseases [36]. Currently, in Viet Nam, many fungicides of microbial origin and antibiotics have been widely used, but the registered and marketed botanical fungicides are still limited.

Table 2. Mode of action of some antimicrobial compounds from plants [37 - 39].

Compound subclass	Compound	Mode of action
Phenols	Catechol	Substrate deprivation
	Eugenol	Effect on membrane/wall, inhibition of biofilm development, effect on mycotoxins synthesis/production, synergistic/antagonistic.
Quinones	Hypericin	Bind to adhesins, complex with cell wall, inactivate enzymes
Flavonoids	Chrysin	Bind to adhesins
	Abyssinone I	Inactivate enzymes
	Epicatechin	Membrane disruption
Terpenoids	Carvacrol	Effect on membrane/wall, effect on cell growth and morphology, inhibition of efflux pump, ROS production anti-nitric oxide, synergistic/antagonistic.
Alkaloids	Capsaicin	Membrane disruption
	Berberine	Intercalate into cell wall and/or DNA
	Piperine	
Tannins	Ellagitannin	Bind to proteins, inhibit enzymes, membrane disruption, substrate deprivation, metal ion complexation.
Coumarins	Warfarin	Interaction with eucaryotic DNA
Lectins	Mannose-specific agglutinin	Inhibit fungal growth and germination
Fatty acid	Hexanoic acid	Induce resistance, Pathogenesis related (PR) genes PR-2, phenolic compounds
Polysaccharides	Laminarin	Induce resistance
	Ulvan	Induce resistance, enhance levels of lignin and phenolic compounds
Polypeptides	Fabatin-2	Form disulfide bridges
Vitamins	Thiamine	H ₂ O ₂ burst, callose deposition, increase levels of flavonoids and phenolic compounds
	Riboflavin	H ₂ O ₂ burst, PR genes
Anthraquinones	Physcion	Induced disease resistance
	Chrysophanol	Induced disease resistance

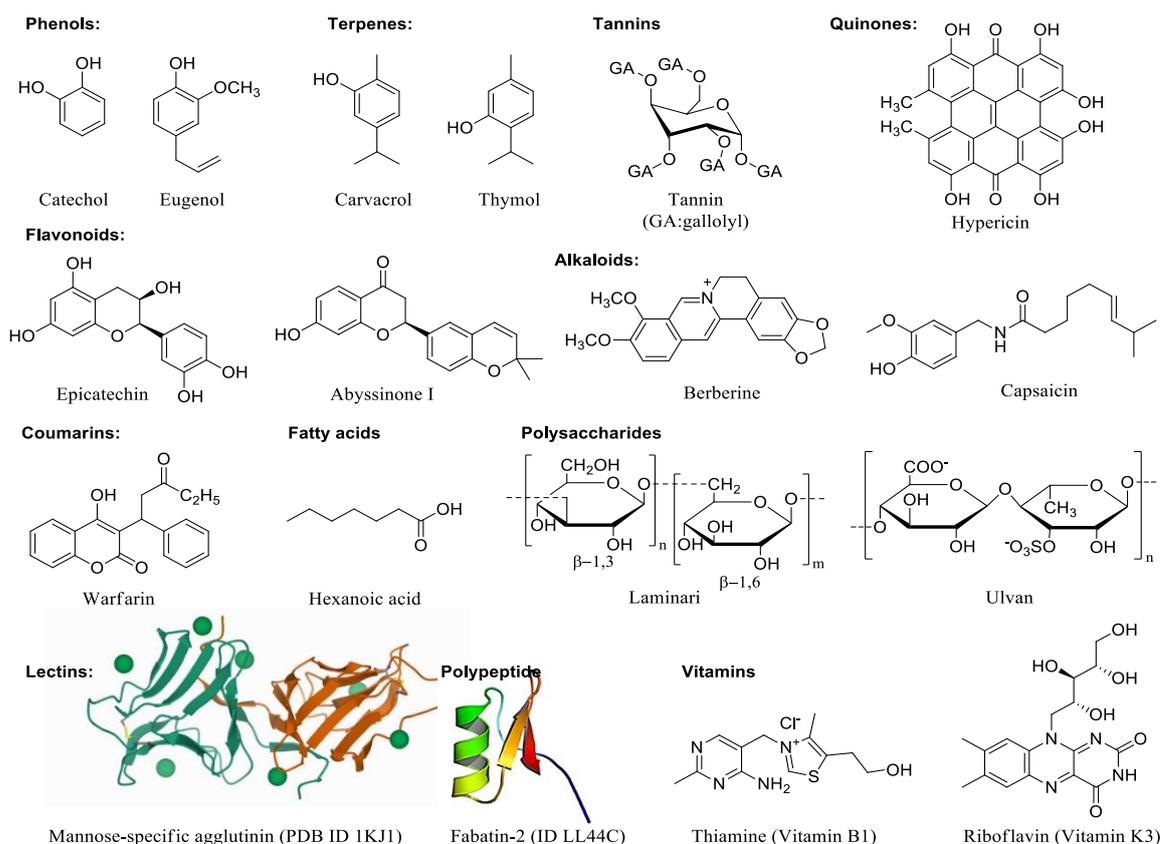


Figure 2. Structures of some antimicrobial plant-derived compounds.

Mode of action of botanical fungicides: The most common plant products used for plant disease management are EOs and extracts. The main chemical constituents are plant secondary metabolites including phenols, flavonoids, quinones, terpenes, tannins, alkaloids, polypeptides, saponins, and lectins which possess antifungal, antibacterial or antioxidant properties (Table 2 and Figure 2). Depending on the type of botanical compound and disease, they have different modes of action.

Many compounds can induce toxicity, inhibit pathogenic fungi or create unfavorable conditions for the formation and growth of pathogenic microorganisms on host plants. They also induce structural modifications of the hypha and mycelia, thus inhibiting the production of substances such as aflatoxin and fumonisin from some fungi like *Aspergillus* spp. and *Fusarium* spp.. This results in reduced pathogenicity of mycotoxin-producing fungal pathogens. The compositions in EOs also have diverse antibacterial activities, including growth inhibition. Some of these inhibit the processes of protein synthesis, increase the permeability of the plasma membrane leading to leakage of substrate in the cell and cause death. For example, the antibacterial activity of *Aloe vera* relies on the presence of substances that denature microbial proteins, disrupting their function. *Aloe vera* contains cinnamic acid which inhibits glucose uptake and production of adenosine triphosphate (ATP). EOs of *Thymus vulgaris* possess antimicrobial activity against *Bacillus cereus*, *Klebsiella pneumonia*, *Staphylococcus aureus*, *Salmonella typhimurim* and *Escherichia coli*. Their activity is attributed to the presence of thymol which makes the bacterial membrane-permeable and depolarizes them resulting in the

interference of cell mechanisms (Tables 3 and 4). Botanical fungicides also inhibit the growth of pathogenic microbials by inducing resistance, namely induced systemic resistance (ISR) or systemic acquired resistance (SAR). They are able to stimulate the production of antimicrobial proteins via a jasmonate (JA)- and ethylene (ET)-sensitive pathway or initiate the necrotizing pathogens, mediated by salicylic acid (SA)-dependent pathway [39].

2.3.1. Phytochemicals with antifungal activities

The first plant-based substance with antifungal activity, having practical applications, was capsaicin, which is found in the Solanaceae family like *Capsicum frutescens*. Capsaicin can be mixed with garlic, mustard, used to control pathogenic fungi such as *Pythium*, *Rhizoctonia*, *Phytophthora*, *Plasmodiophora*, *Sclerotium* [40].

Table 3. Antifungal activity of some botanical products [36]

Plant products/compounds	Controlled plant pathogenic fungi
<i>Plant extracts</i>	
Extracts of acacia, sapodilla, datura, eucalyptus, pomegranate, black plum	<i>Aspergillus candidus</i> , <i>A. flavus</i> , <i>A. fumigatus</i> , <i>A. ochraceus</i> , <i>A. niger</i>
Extracts of eucalyptus, lavender	<i>Alternaria alternata</i>
Extracts of clove, cinnamon, ginger, black pepper, garlic, onion	<i>Aspergillus niger</i>
Extracts of neem tree, garlic, turmeric	<i>Fusarium oxysporum</i> , <i>Rhizoctonia solani</i>
Extracts of artemisia, thyme, eucalyptus	<i>Fusarium solani</i>
Extracts of Indian beech, milkweed, oleander, turmeric	<i>Aspergillus fumigatus</i> , <i>Alternaria solani</i>
Extracts of kokum, wild turmeric, jasmine	<i>Rhizopus stolonifer</i> , <i>Colletotrichum coccodes</i>
Extracts of <i>Jatropha</i> spp.	<i>Alternaria alternata</i> , <i>Fusarium oxysporum</i> , <i>Rhizoctonia solani</i> , <i>Aspergillus</i> spp., <i>Trichoderma viride</i>
<i>Compounds</i>	
Citral, eugenol, geraniol	<i>Fusarium moniliforme</i> , <i>Curvularia lunata</i>
Carvacrol, eugenol, citronellol, geraniol, citral, perillyl, menthol	<i>Monilinia fructicola</i> , <i>Botrytis cinerea</i>
Thymol, carvacrol, 1,8 cineole, γ -terpinene, <i>p</i> -cymene, anethole	<i>Fusarium moniliforme</i> , <i>Rhizoctonia solani</i> , <i>Phytophthora capsici</i>
<i>Essential oils</i>	
Essential oils from thyme, rosemary, mint, basil, sage)	<i>Botrytis cinerea</i>
Essential oils from anise, cumin, caraway, pennyroyal, thyme, cinnamon	<i>Aspergillus flavus</i> , <i>Botrytis cinerea</i> , <i>Alternaria alternata</i>

Among the most studied and used botanical fungicides in the world, garlic (*Allium sativum* L.) has long been discovered to have antibacterial properties, but the main active ingredient, allicin (diallylthiosulfinate), was newly identified by Cavallito in 1944 [41]. Allicin was effective against four species of fungi, *Fusarium oxysporum*, *Botrytis cinerea*, *Verticillium dahliae* and *Phytophthora capsici*. In 2005, saponins from quinoa (*Quillaja saponaria*) were approved by the US EPA for use as biofungicide for a broad range of bacterial, fungal and viral diseases of plants

[42]. Regarding enhancing the resistance mechanism, *Reynoutria sachalinensis* extract, a well-known active ingredient of Milsana® fungicide, stimulates salicylic acid (SA)-dependent defense responses in courgette against powdery mildew caused by *Podosphaera xanthii* [43], while *Ulva armoricana* and *Ulva lactuca* extracts express pathogenesis related genes, enhance levels of lignin and phenolic compounds in bean, grapevine, cucumber or tomato against powdery mildew caused by *Erysiphe polygoni*, *Erysiphe necator*, *Sphaerotheca fuliginea* or the pathogen caused by *Fusarium oxysporum* f.sp. *lycopersici* [44].

2.3.2 Plant essential oils with antifungal activity

In recent years, the potential of EOs to control plant diseases is of great interest. EOs with diverse bioactivity (antifungal, antibacterial, etc.) and biodegradable property have a wide range of applications in crop protection and post-harvest disease management. Some EOs are marketed as natural fungicides for organic agriculture production (Tables 3 and 4). These include jojoba oil *Simmondsia californica* (E-Rase™), rosemary oil *Rosemarinus officianalis* (Sporan™), thyme oil *T. vulgaris* (Promax™), etc. [2].

Table 4. General mechanism on fungi of some plant essential oils [38]

Mode of actions	Essential oils
Effect on membrane/wall	<i>Cinnamomum</i> , <i>Citrus</i> , <i>Coriaria nepalensis</i> , <i>Coriandrum sativum</i> , <i>Juniperus communis</i> , <i>Litsea cubeba</i> , <i>Melaleuca alternifolia</i> , <i>Mentha piperita</i> , <i>Ocimum basilicum</i> , <i>Origanum</i> , <i>Salvia sclarea</i> , <i>Syzygium aromaticum</i> , <i>Thymus</i>
Effect on cell growth and morphology	<i>Eucalyptus</i> , <i>Thymus</i> spp.
Inhibition of efflux pump	<i>Cinnamomum</i> , <i>Citrus</i> , <i>Eucalyptus</i> , <i>Melaleuca alternifolia</i> , <i>Mentha</i> , <i>Ocimum basilicum</i> , <i>Origanum vulgare</i> , <i>Thymus vulgaris</i>
Action on fungal mitochondria	<i>Anethum graveolens</i> , <i>Artemisia herba alba</i> , <i>Cananga odorata</i> , <i>Cinnamomum camphora</i> , <i>Coriandrum sativum</i> , <i>Commiphora myrrha</i> , <i>Hedychium spicatum</i> , <i>Origanum compactum</i> , <i>Origanum majorana</i>
ROS production anti nitric oxide	<i>Zatharia multiflora</i>
Inhibition of biofilm development	<i>Coriandrum sativum</i> , <i>Croton cajucara</i> , <i>Cymbopogon</i> , <i>Cytrus</i> , <i>Eucalyptus</i> , <i>Laurus nobilis</i> , <i>Litsea</i> , <i>Melaleuca alternifolia</i> , <i>Mentha</i> , <i>Myrtus communis</i> , <i>Ocimum</i> , <i>Piper claussonianum</i> , <i>Rosmarinus officinalis</i> , <i>Syzygium aromaticum</i>
Anti quorum sensing	<i>Citrus</i> , <i>Juniperus communis</i> , <i>Mentha piperita</i> , <i>Origanum</i> , <i>Salvia sclarea</i>
Effect on mycotoxins synthesis/production	<i>Cinnamomum</i> , <i>Origanum vulgare</i> , <i>Cymbopogon</i> , <i>Cider</i> , <i>Citrus</i> , <i>Eucalyptus</i> , <i>Mentha</i> , <i>Ocimum sanctum</i> , <i>Rosmarinus officinalis</i> , <i>Satureja hortensis</i> , <i>Thymus</i> , <i>Zataria multiflora</i>
Synergistic/antagonistic	<i>Citrus</i> , <i>Coriandrum sativum</i> , <i>Cymbopogon nardus</i> , <i>Eucalyptus</i> , <i>Illicium verum</i> , <i>Lavandula angustifolia</i> , <i>Matricaria recutita</i> , <i>Melaleuca alternifolia</i> , <i>Myrthus</i> , <i>Ocimum basilicum</i> , <i>Origanum heracleoticum</i> , <i>Pelargonium graveolens</i> , <i>Rosa damascene</i> , <i>Satureja hortensis</i> , <i>Thymus vulgaris</i> , <i>Viola odorata</i>

Many investigations have reported the effectiveness of plant-derived products in controlling fungal growth and mycotoxin production, e.g., cinnamon oil, clove oil, marjoram oil, rosemary oil, tea tree oil, thyme, cinnamon and anise oil. Thymol and carvacrol were the most effective components against most of the tested fungal species [38]. The ether and ester derivatives of carvacrol have antifungal, antibacterial, and antifungal activities, of which carvacryl ester has the strongest antibacterial activity [45]. Some plant EOs also have a synergistic effect, for example, a mixture of volatile oils (citronella oil, pine oil, citrus oil, eucalyptus oil, camphor oil, peppermint oil, cinnamon oil) with non-volatile oils (vegetable oil, cottonseed oil, soybean oil, rapeseed oil) has a synergistic effect on the control of vegetable diseases and spiders [46].

In the management of post-harvest diseases of stored products like vegetables and fruits, many essential oils with antifungal and antibacterial activity have been discovered and applied in practice, of which most are essential oils from aromatic and medicinal plants [14, 47].

Recently in Viet Nam, a number of botanical fungicides have been registered such as Citrus oil (Map Pacific PTE Ltd.), basil essential oil, eugenol (Guizhou Company, China); eugenol (Truong Thinh Company); and the mixture of tangerine oil, lemongrass oil, basil oil, lemon oil (Thanh Phuong Company) [48]. However, the products consumed in the market are still limited.

2.4. Botanical herbicides

In fact, weeds cause a greater reduction in crop yields even more than pests do. Therefore, modern agriculture cannot be without the use of herbicides. The demand for herbicides is increasing day by day. Today, herbicides account for more than half of all pesticides used in developed countries. But from that also arise the phenomenon of protest and environmental pollution. In the strategy of sustainable agriculture development, botanical herbicides are prioritized for application. However, they have only been of interest since the 1990s and have flourished in recent years. In contrast to synthetic products, botanical herbicides often have broad-spectrum activity, little or no selectivity, and must be used in relatively large amounts. Botanical herbicides include some of the following compounds:

Fatty acids: Some fatty acid salts are commercially available as non-selective, relatively fast-acting herbicides. However, most weeds tend to recover after being treated with fatty acids because the activity of the product does not last long. Among the medium-chain fatty acids, caprylic acid (C8) and pelargonic acid (C9) are the most effective herbicides. Besides the fungicidal effect, esters of pelargonic acid in pelargonium oil are also an annual herbicide with low toxicity and no residue. In the series of saturated fatty acids, C9 - C11 acids have particularly high herbicidal activity. Potassium salts of fatty acids (up to 40 %) are commercially available, effective non-selective herbicides used to control mosses and algae. Oleic acid is often the main ingredient in these mixtures, although the exact composition of the products is not published [49].

Essential oils: The potential application of EOs as herbicides is enormous. Most of the natural EOs used in weed management are mixtures, difficult to cover the formulations available, so it is necessary to use more surfactants. Several multi-active botanical herbicides have been discovered and applied in practice. For example, Rocaglamide obtained from bark extract of *Aglaia congylos* (Meliaceae) has insecticidal, fungicidal and pre- and post-emergent activity [30]. Eugenol from basil oil is the main active ingredient in Clove Oil, a trade name product of EcoSMART Technologies, Inc., used to control weeds and fungi [2].

The use of EOs for weed control in organic agriculture seems promising. The most commonly used EOs are pine oil, clove oil, lemongrass oil and peppermint oil. But these natural herbicides act very rapidly and their efficacy is limited by their high volatility. Alternative formulations, such as microencapsulation are being developed to reduce the dosage applied, limit decomposition and increase the effective application [50].

In Viet Nam, until 2020, there are very few registered botanical herbicides based essential oils, for example: “Nosiquat 0.2SL” with 1.8-cineole as an active ingredient [48].

Allelochemicals: Allelopathy is a biological phenomenon in which a plant produces one or more biochemicals that affect the germination, reproduction, and growth of neighboring plants. These biochemical compounds are called allelochemicals or allelopathins. They disrupt various physiological processes in plants such as photosynthesis, respiration, water balance and hormones. The mode of action of allelochemicals is similar to that of synthetic herbicides, which has allowed them to be considered for possible use in weed management as bioherbicides. The main mode of action is the inhibition of enzyme activity, causing suppression or retardation of plant growth and/or seed germination. Using allelochemical secreted by plants to inhibit the growth and development of invasive weeds is an advanced method because it does not use any chemical and is environmentally friendly, very suitable for organic agricultural production. Allelochemicals are diverse chemical groups including phenolic compounds (simple phenolics, flavonoids, coumarins, and quinones), terpenoids (monoterpenes, sesquiterpenes, diterpenes, triterpenes, and steroids), alkaloids, and many other chemical families. In nature, some plants exhibiting allelopathy through secreting allelochemicals such as sorghum, rice, sunflower, rapeseed, wheat, etc., can be planted or intercropped with other crops to prevent and clean weeds [50].

Some allelochemicals present in the plant have been identified as linoleic acid and its methyl esters, allyl isothiocyanate, *p*-hydroxybenzoic acid, 1,8-cineole, α -pinene, γ -terpinene, α -terpineol, *R*-limonene, sesamol, sesamin, *L*-tryptophan. Typically, sorgoleone, secreted from the roots of the sorghum plant *Sorghum bicolor*, is as effective as some synthetic herbicides such as metribuzin, diuron and atrazine. Sorgoleone is a typical allelochemical with photosynthetic inhibition activity in young seedlings and activity at other molecular target sites in older plants. 4.6 % WP formulation product has a strong inhibitory effect on germination and growth of horsetail grass (*Phalaris minor*), lulu grass (*Solanum nigrum*), owl grass (*Cyperus rotundus*), ragweed (*Ambrosia artemisiifolia*) and cassava (*Cassia obtusifolia*). Momilactone, an allelochemical isolated from the roots of rice (*Oryza* spp.) is a growth inhibitor of common weeds in rice fields such as *Echinochloa colona*, duckweed (*Amaranthus lividus*), etc. [51]. However, its mode of action is still unknown.

3. CHALLENGES AND TRENDS IN BOTANICAL PESTICIDE DEVELOPMENT IN ORGANIC FARMING IN VIET NAM

3.1. Challenges

Limitation of botanical pesticides: Although having many advantages compared to conventional pesticides, the quantity of commercial botanical pesticides remains low. The main limitations are:

- The source of plant material is available but scattered, making it difficult to ensure sufficient supply for industrial-scale production.

- Product quality is unstable because their composition and content containing in plants depend on many factors such as geographical location, climatic and farming conditions, harvesting process, etc. In addition, the content of active ingredients in the plant is low, leading to the difficulties in extraction and formulation process. As a result, the product cost is high.
- Most isolated compounds from plants are unstable in the environment, easily decomposed by light, high temperature, humidity, so it is difficult to store.
- Many botanical pesticides are inferior to synthetic pesticides in some respects, such as quantities required, more slow-acting. They cannot make a significant contribution in cases of sudden, widespread and devastating diseases and catastrophic plagues of insect pests [50].
- Many published studies but only a few practical results.

Challenges of using botanical pesticides in Viet Nam: The use of environmentally friendly, natural agrochemicals are recommended for organic agricultural production. It is a big challenge for Viet Nam because at present, most of the pesticides being used are synthetic, toxic to the environment and community while the awareness of environmental protection is still limited.

Climate change has affected the ecosystem, biodiversity and directly impacted agricultural production by reducing farming acreage, changing cultivation conditions, increasing diseases and causing new harmful pests to appear. These challenges require Viet Nam to transform its agricultural production methods towards adaptation and environmental sustainability.

Viet Nam has a very rich source of plant materials with many species containing diverse and high biologically active compounds. Utilizing this source of materials, it is possible to create agrochemicals of natural origin, including botanical pesticides with high use value, for sustainable agricultural development.

3.2. Trends in the development of botanical pesticides

In Viet Nam, botanical pesticides have been interested and researched for many years, but the number of commercialized and used products is very small due to their limitations and the lack of suitable technologies. It is necessary to develop a systematic strategy, starting from the screening, identification, selection of plant materials and production technology to the implementation of product commercialization and changing the awareness of farmers.

Research on bioactive compounds from plants and their applications: In general, the research pipeline of active compounds for botanical pesticides includes the following steps: Searching, in vitro screening and separating highly bioactive compounds from plants, in vivo bioassay by the whole plant methods, field trials, application in crop protection of organic agricultural production and post-harvest management.

Viet Nam has many species of plants containing bioactive compounds used as botanical pesticides but only some have potential application. Therefore, it is necessary to screen and select certain potential plants, which can serve as raw materials for studies and can meet the following criteria: available and easy to collect; highly active against many pests in Vietnam; active constituents with high content, relatively stable to environmental conditions, etc. The researchers of botanical pesticides in Viet Nam should pay attention to aromatic and medicinal plants containing bioactive compounds that control insects by non-toxic mechanisms (repellents, attractants, IGRs, etc.) and to EOs with antifungal, antibacterial activity used in crop protection and postharvest diseases management. Some products or compounds should be interested in

practical application research such as azadirachtin, matrine, allicin, saponins, anacardic acid, alginate, and essential oils from spices and medicinal plants, such as basil, cinnamon, mint, basil, lemongrass, eucalyptus, etc. for crop protection and postharvest pest control or allelochemicals with growth inhibitor activities on weed species.

Research and production of natural additives used in pesticide formulation technology: Screening, searching and using plant-based additives in pesticide formulations, such as solvents, carriers, surfactants, stabilizers, synergists and other additives, fixatives with biological activity enhancement (enhancing pesticide performance, increasing repellency and attractive duration), and adjuvants for controlled release formulations. In particular, they are available in plants in Viet Nam and are almost non-toxic and environmentally friendly. This is also a trend with a lot of application potential.

Development and application of new types of pesticide formulation: These new types of the formulation can increase pest control activity. For example, slow-releasing technology, encapsulation technology, and nanotechnology could create environmentally friendly pesticide products, reducing the applied doses on-field and using natural coating agents, carriers, stabilizers such as chitosan, aloe vera gel, cellulose, modified starch, seaweed products, and some available essential oils from Viet Nam biomass resources.

3.3. Application of nanotechnology in botanical pesticide formulations

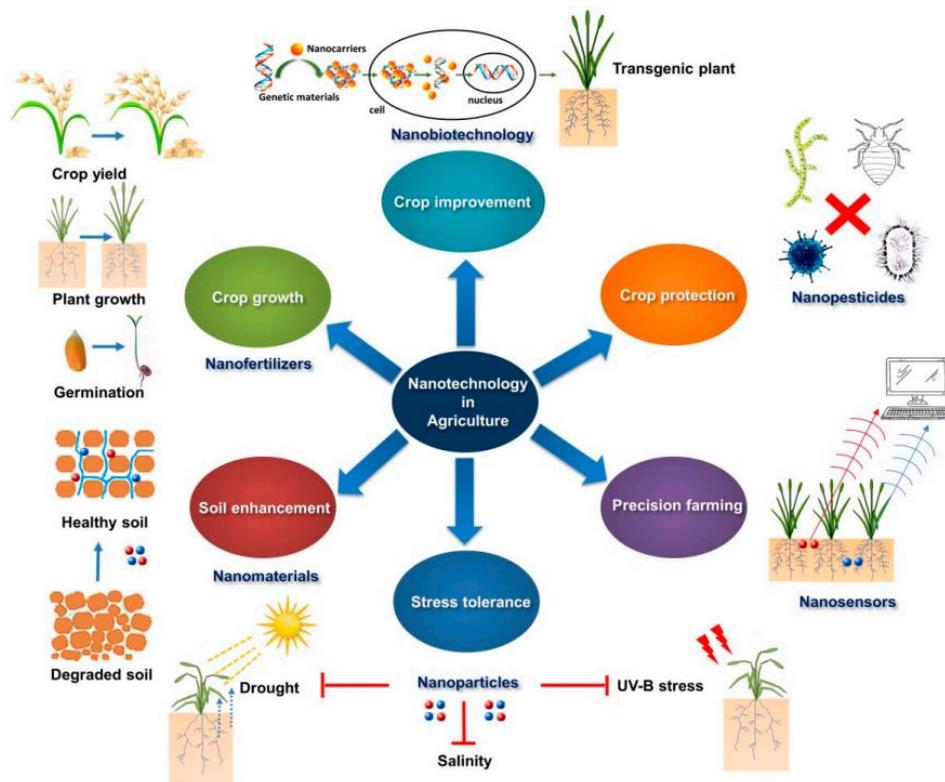


Figure 3. Application of nanotechnology in agriculture (graphic is taken from reference [52]).

Nanotechnology could create new materials with special properties, used in many fields of manufacturing. In recent years, the application of nanotechnology in agriculture is considered as a new trend in the development of sustainable agriculture. Nanotechnology can be employed in most stages in agriculture such as fertilizer and pesticide production, post-harvest management, monitoring and control of smart agriculture, etc (Figure 3). It is much cheaper and easier to develop and apply nanotechnology in agriculture than in other fields [53, 54].

In the field of plant protection, nanotechnology can be applied for many purposes, in which, some applications are potential to improve the use of botanical pesticides. Pesticides containing nano-active ingredients have unique physical and chemical properties which lead to the ramping on efficiency. Insoluble AIs in nano-size can easily disperse in solutions and interact better with targeted objects. In pesticide formulation technology, microemulsions and formulation with nanomaterials (nanof ormulation) allow a significant increase in water solubility, dissolution rate, dispersion uniformity upon application while no chemical alteration to insecticide molecule is actually made. Nanoparticles help slow-release active ingredients, limiting evaporation and decomposition by the environment. Nanosuspension and nanodispersion can increase the toxicity of the products because of the size distribution and surface morphology. In addition, active ingredients combining with Si, Ag, TiO₂ nanoparticles in microcapsules help the pesticides decompose quickly in soil and plants [54, 55].

However, some of the negative ecological and environmental impacts caused by the nanoparticles are related to the chemical hazard to edible plants after treatment with high concentrations of Ag nanoparticles. In some cases, nanomaterials generate free radicals in living tissues that lead to DNA damage. Therefore, nanotechnology needs to be carefully evaluated before applying it to agriculture [53].

Although Viet Nam has just approached nanotechnology in recent years, there have been initial results in the field of sustainable agricultural development. Translation of researches into practice must take more time indeed.

4. CONCLUSIONS

The goal of sustainable agricultural development is not only to increase product quantity as well as productivity but at the same time provide safe products for human health and reduce negative impacts on the environment. To achieve that goal, the effective use of plant-derived compounds in plant protection plays a very important role. Vietnam's tropical climate is favorable for arising and growing of many harmful insects and fungi. On the other hand, Viet Nam has the advantage of abundant plants, which is a source of diverse EOs and plant extract products containing biologically active compounds. They can be used to research and produce many environmentally friendly botanical pesticides, serving organic agriculture production and sustainable economic development.

CRedit authorship contribution statement. Author 1: Conceptualization, Writing - Original Draft, Data analysis. Author 2: Conceptualization, Methodology, Writing. Author 3: Conceptualization, Methodology, Review and Editing. Author 4: Review and Editing. Author 5: Supervision, Review.

Declaration of competing interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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